Active Laser Ranging along with Lasercom
- Field Emulation -

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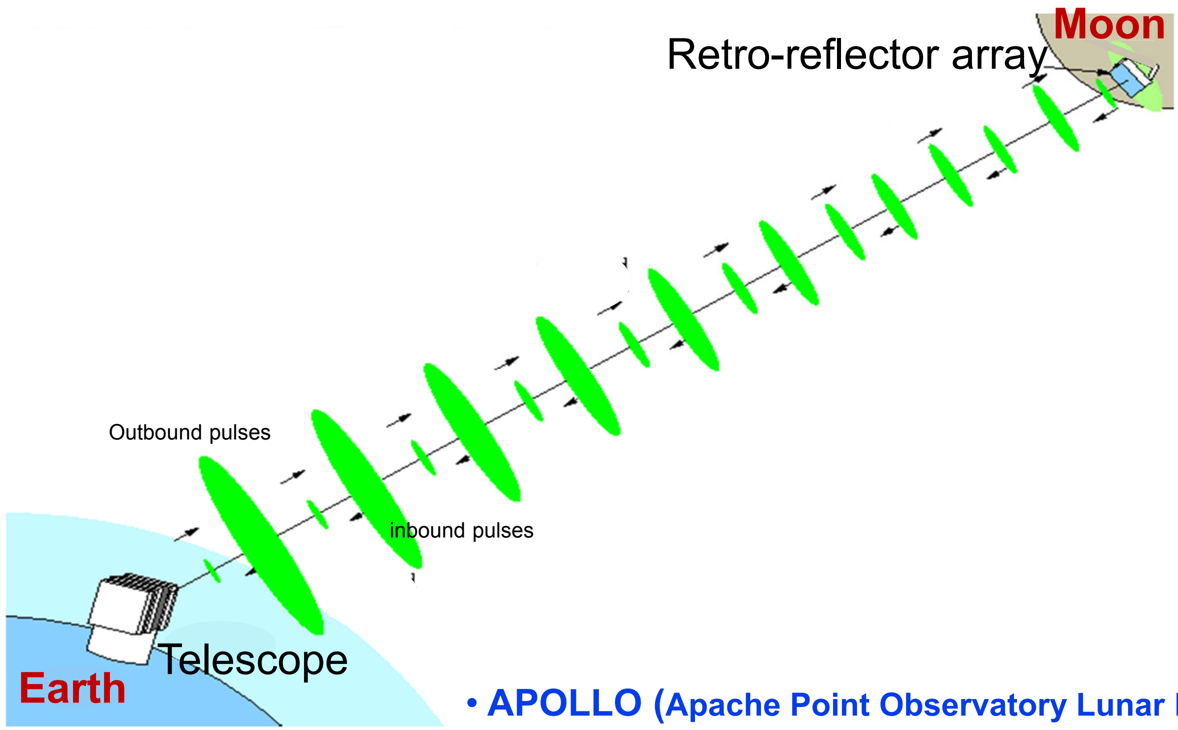
OUTLINE

- Motivation
- Passive laser ranging versus active laser ranging
- Approach
- Lab experiment
- Field test
- Conclusions

MOTIVATION

- **Interplanetary laser ranging will advance fundamental physics and solar system dynamics**
- **Precision ranging will enable**
  - Tests of gravity
    - Explaining the apparent acceleration of the expansion of the universe
    - Possible existence of extra dimensions
    - Reconciliation of quantum mechanics with gravity
  - Determination of the Shapiro time delay due to solar gravity (from measurement of the Earth-Mars distance near solar conjunction)
  - Test of the equivalence principle in the Earth-Mar-Sun-Jupiter system
- **Improve understanding of dynamics of solar system, its history and future evolution**
  - Improved knowledge of planetary orbits and locations (currently ~100 m)
  - Improved understanding of rotation of planets and influence of oceans, atmospheres, etc
  - Gravity field of Sun, particularly degree 2-terms (flattening and equatorial shape)

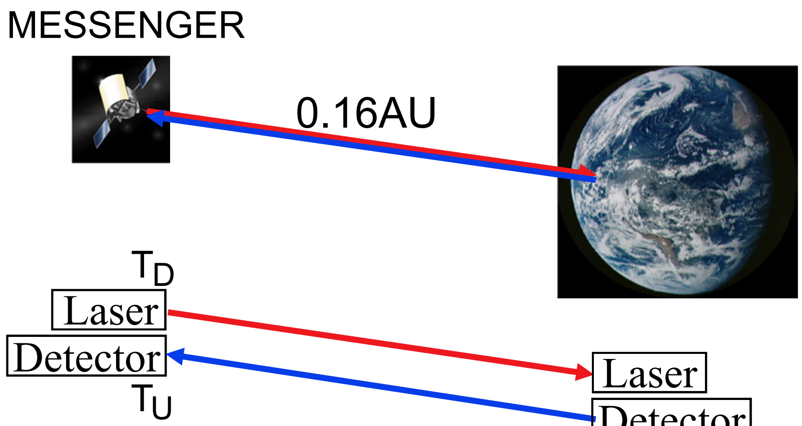
LIMITATION OF PASSIVE LASER RANGING

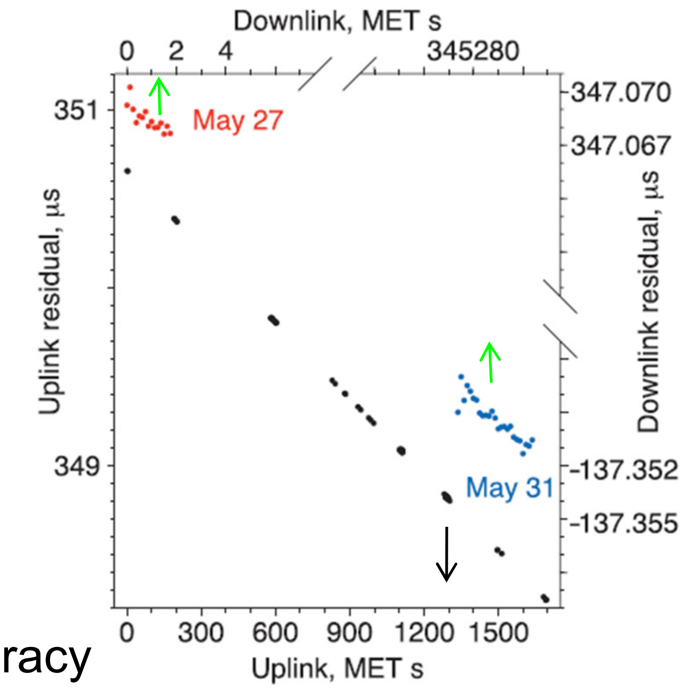


- **APOLLO (Apache Point Observatory Lunar Laser-ranging Operation)**
- **MLRS (McDonald Laser Ranging Station)**

- **Ordinary passive ranging (~1/R^4) to corner cubes of the moon is realistically about the maximum distance for laser ranging with millimeter accuracy**
- **Active laser ranging with two terminals can extend ranging (~1/R^2) beyond the moon to planets**

TWO-WAY LASER LINK OVER INTERPLANETARY DISTANCE





- RMS precision – 0.4m, limited by space clock accuracy

$$\begin{array}{r} \text{Down link time} \\ \text{Up link time} \end{array} \begin{bmatrix} \tau_D \\ \tau_U \end{bmatrix} = \begin{bmatrix} T_D + R \\ T_U - R \end{bmatrix} = (p_1 + p_2 t) \pm \left(p_3 + p_4 t + p_5 t^2 + O(t)\right)$$

$T_{D/U}$ and t - MET (mission elapsed time) synchronized to coordinated universal time

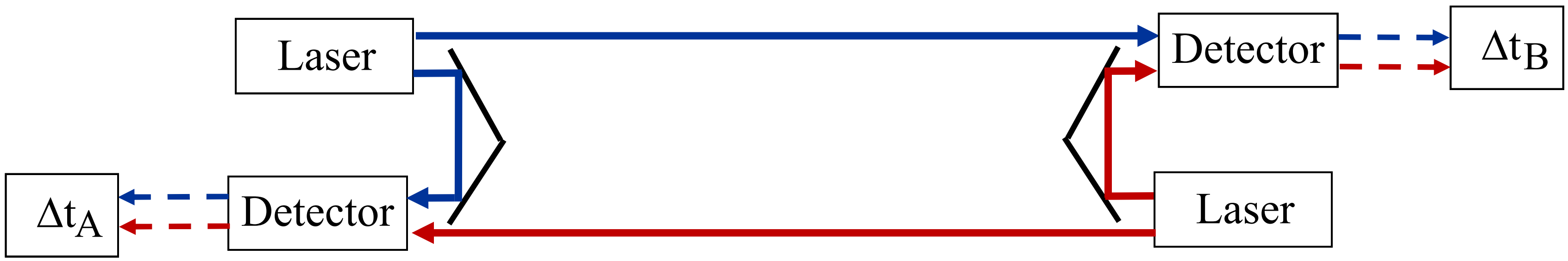
R – one way range

Parameter	Laser link solution	Spacecraft ephemeris	Difference
Range (m)	23,964,675,433.9 ± 0.2	23,964,675,381.3	52.6
Range rate (m s^{-1})	4,154.663 ± 0.144	4,154.601	0.062
Acceleration (mm s^{-2})	−0.0102 ± 0.0004	−0.0087	−0.0015
Time (s)	71,163.729670967 ± 6.6 × 10^{-10}	71,163.730019659	0.000348692
Clock drift rate (ppb)	1.00000001559 ± 4.8 × 10^{-10}	1.00000001564	−3.2 × 10^{-10}

- Ranging between Mercury Laser Altimeter and Earth
- D. E. Smith et al, Science vol. 311, p.53, (2006)

APPROACH - ARCHITECTURE

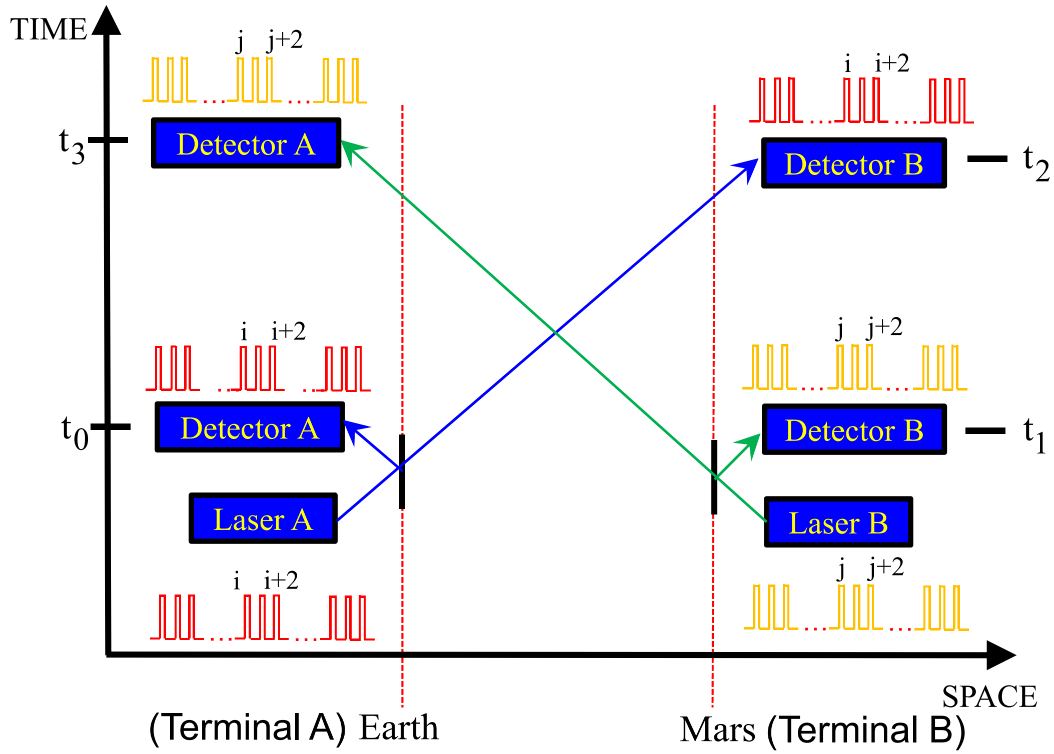
- **To overcome space clock limitation,**
  - **Avoid use of space clock**
  - **Use local references**



Terminal A

Terminal B

APPROACH - SYNCHRONIZATION



- Range estimated from 4 time tags on two terminals:

$$R=[t_3(j)-t_0(i)+t_2(i)-t_1(j)]c/2$$

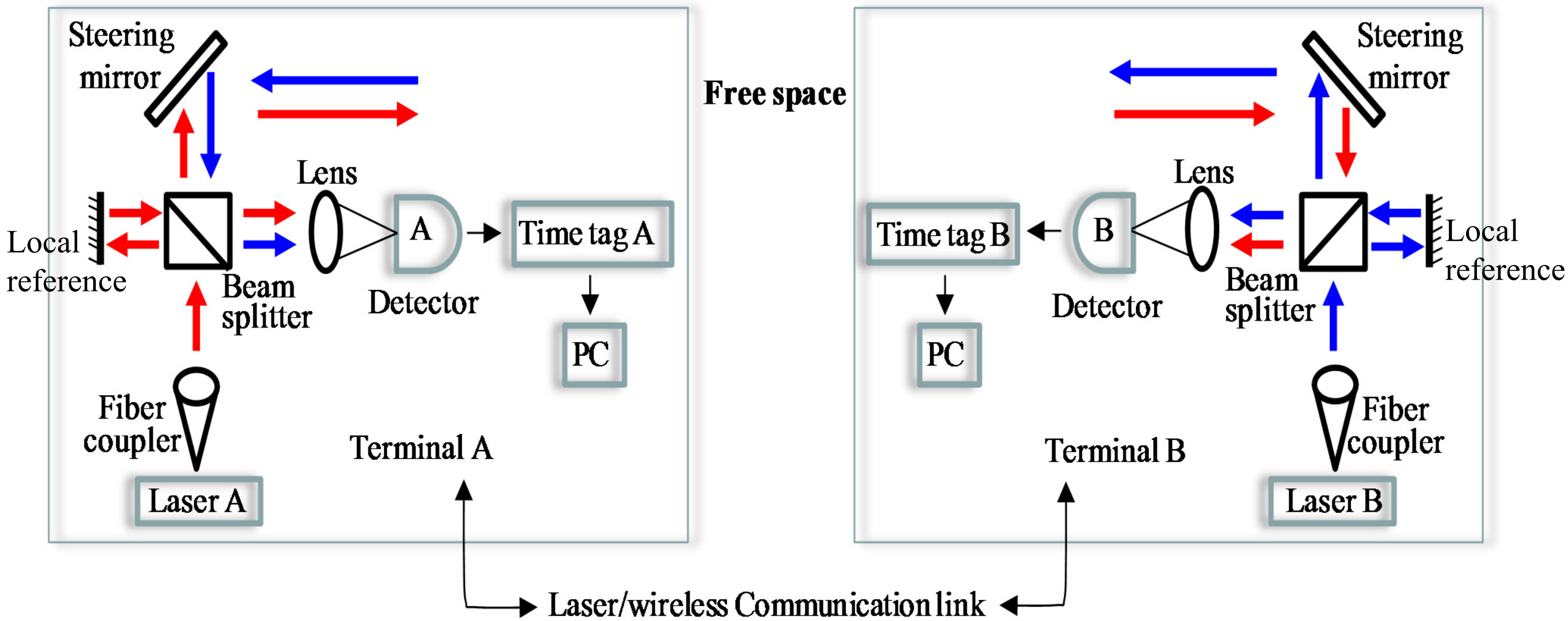
- c – speed of light. Correction on clock difference on two time tag devices

$$\Delta t_A=\alpha\Delta t_B \qquad \alpha = \frac{1}{2}\left[\frac{t_3(j+1) - t_3(j)}{t_1(j+1) - t_1(j)} + \frac{t_0(i+1) - t_0(i)}{t_2(i+1) - t_2(i)}\right]$$

APPROACH - SYNCHRONIZATION

- Synchronize without using space clock or common clock/trigger
- Launch two different coded sequences of pulses from the two lasers
- Send the time tags from one terminal to the other using optical or RF communication
- Compare the coded sequence received locally with that from the remote terminal to identify the origin of each detection event (Earth terminal or Mars terminal)
- Range is estimated from $R=[t_3(j)-t_0(i)+t_2(i)-t_1(j)]c/2$

LABORATORY EXPERIMENT DESIGN



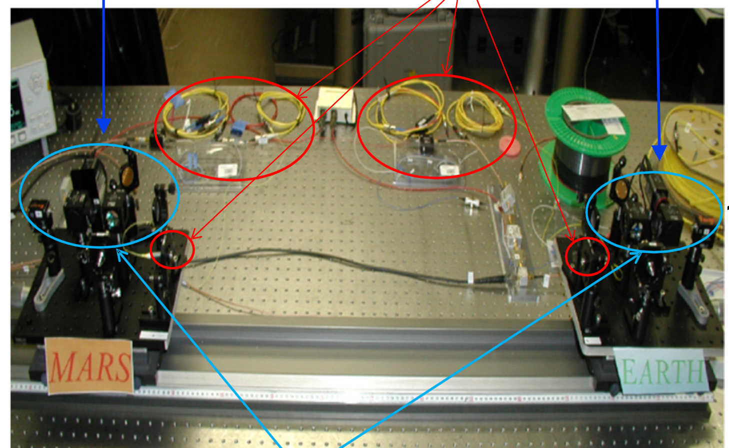
LABORATORY EXPERIMENT SETUP

Jet Propulsion Laboratory
California Institute of Technology

Wireless communication

Fiber optics based terminals

1550nm



1064nm

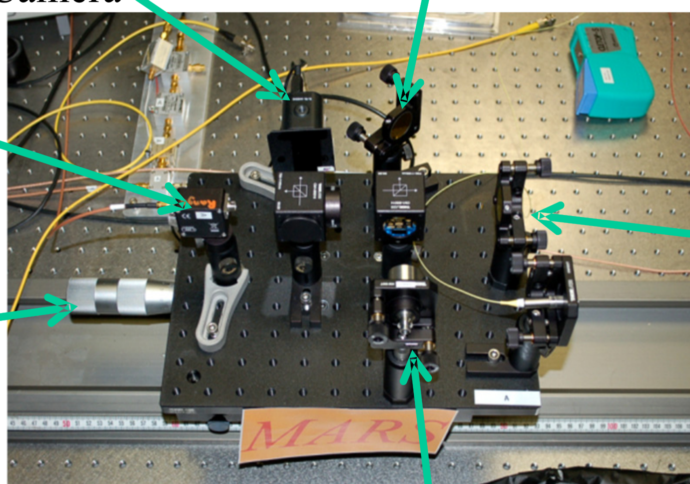
Conventional bulk optics based terminals

Input/Output Steering

Alignment Camera

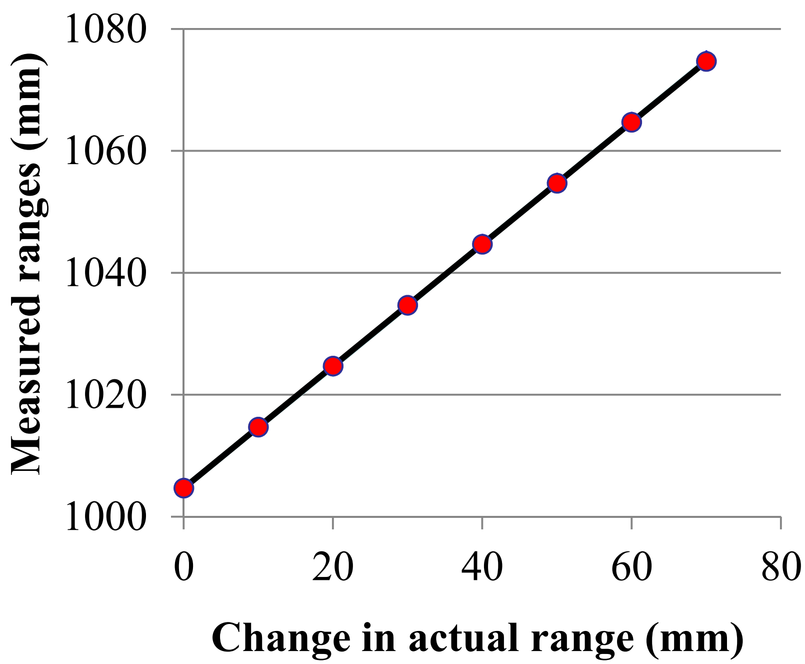
PIN Detector

Fine Range
Adjustment

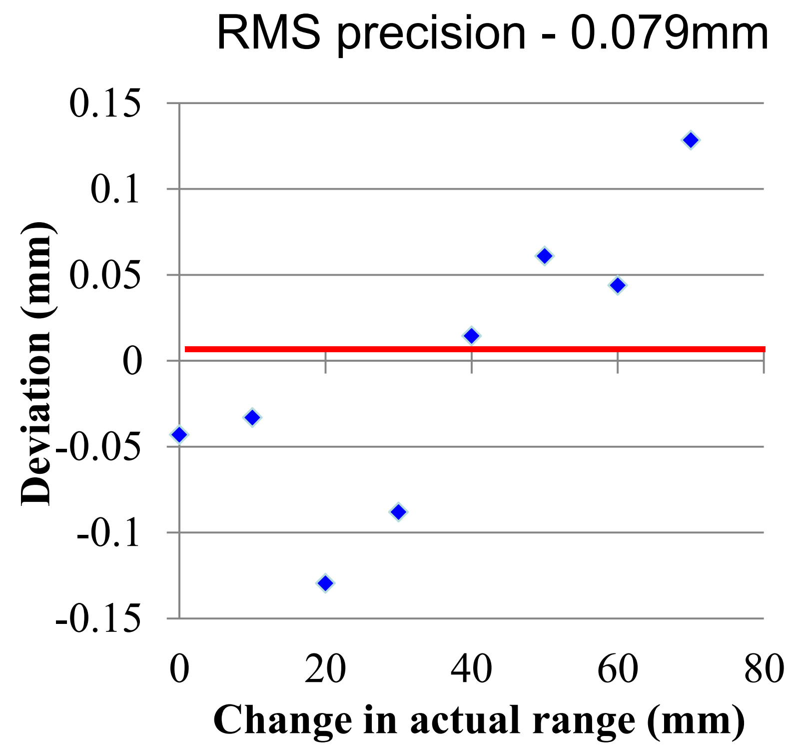


Local reference

Laser Input Coupler

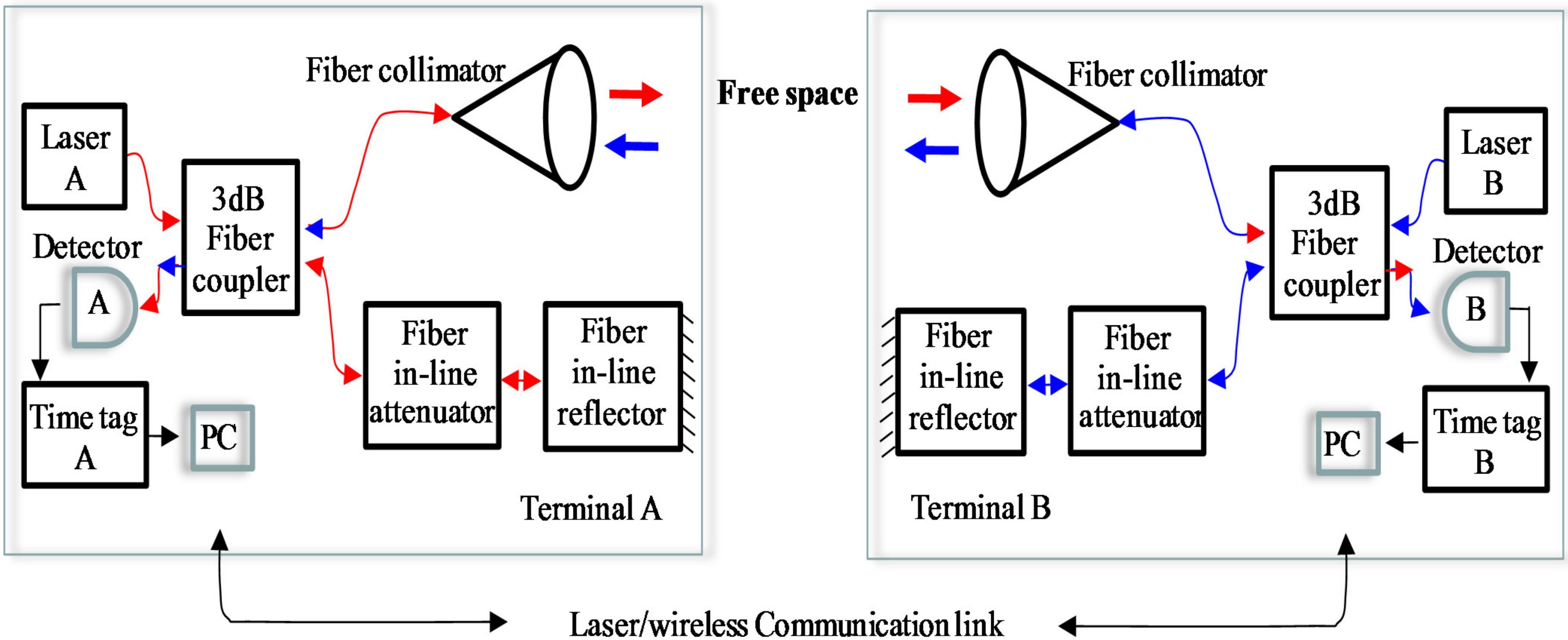


(a) Measured range vs. the actual change in range from translation of the terminals. The experimental results are indicated by the filled circles in red. The black curve is a line with a unit slope and an offset chosen to minimize deviation from the data



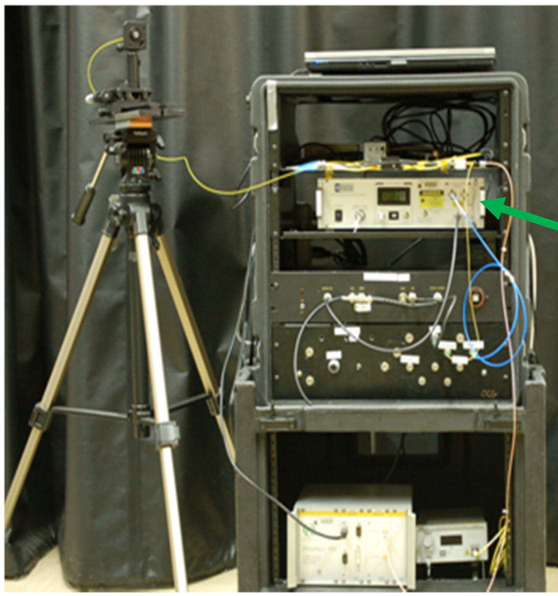
(b) Deviation of the measurements in (a) from the line. Blue diamonds indicates the experimental results. Each data point represents 1000 sample measurements.

FIELD TEST ARCHTECHURE



- Fiberoptic-based terminals to avoid internal alignment change while aligning to point at each other

FIELD TEST SETUP

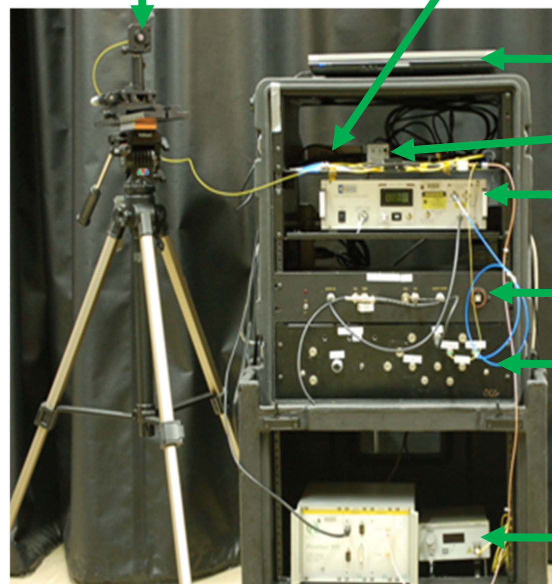


laser 1550nm

Terminal A

Fiber collimator launching/receiving head

Fiber coupler



Laptop

APD

Laser 1064nm

FPGA

Modulator

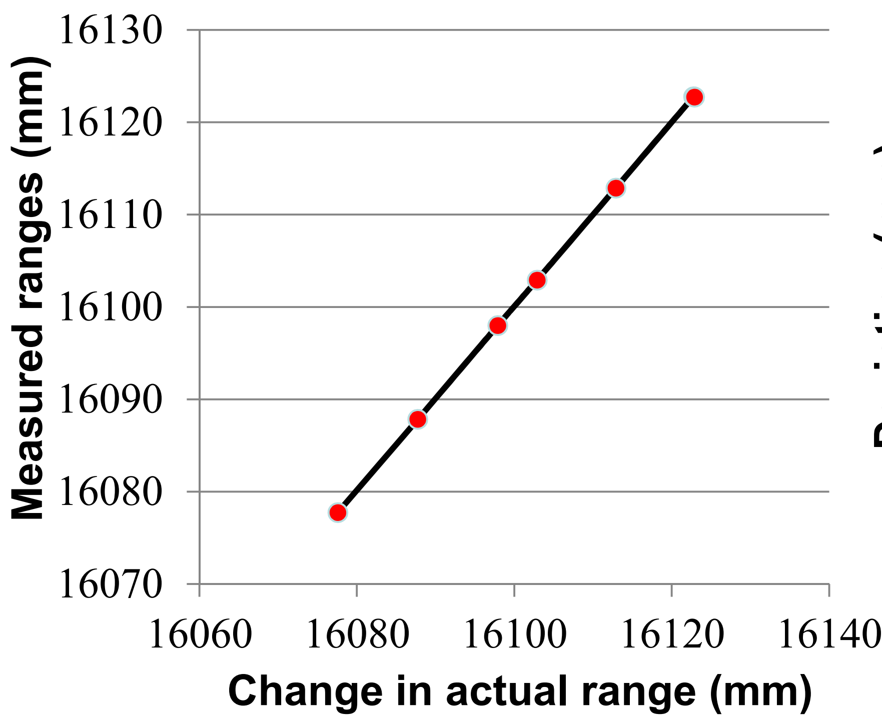
Alignment laser

Time tag device

Terminal B

Wireless communication

FIELD TEST RESULTS



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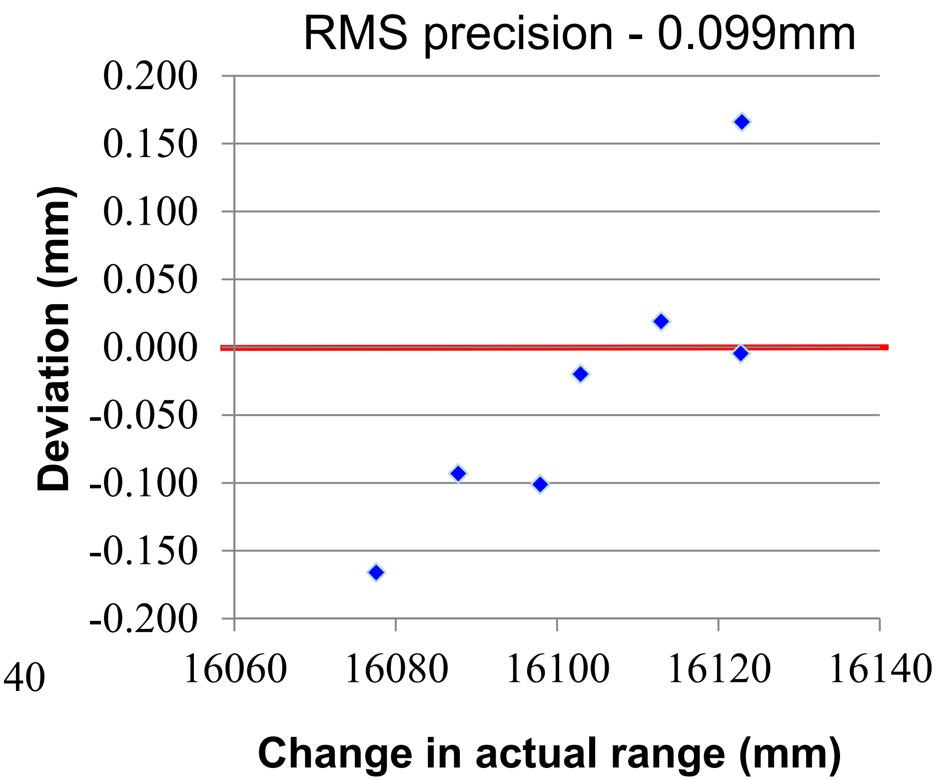

(b) Deviation of the measurements in (a) from the line. Blue diamonds indicates the experimental results. Each data point represents 1000 sample measurements.

SUMMARY

- Demonstrated the real-time active laser ranging using a method applicable to interplanetary distances

- Sub-millimeter ranging accuracy has been achieved with the systems built from off-the-shelf commercial components, demonstrating the robustness of the scheme

- The experimental results indicate that active laser ranging can be implemented for interplanetary distances to meet the goal of 1mm ranging accuracy, including the effects of the Earth's atmosphere

- Paves the way for advances in the study of fundamental physics and solar system dynamics